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# Developing cultivars to face climate change effects on crops and weeds. A review

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**Abstract**

Climate change caused by the release of greenhouse gases in the atmosphere due to various anthropogenic activities will impact many aspects of the human and natural world, but effects on agricultural production could be of particular significance. Estimates of annual damages in agriculture due to temperature increase or extended periods of drought, for example, will be more costly compared to those in other sectors and activities. Yield losses, as a result of climate change, are caused either through the direct effects of climate change components on crops or through indirect effects such as increased inputs in crop production necessary for the control of weeds, for example. To counteract the effects of climate change various adaptation strategies have been suggested. It has been suggested by several authors that the farmers' primary response to climate change would be to seek and crop cultivars that are most adapted to highly variable, extreme climatic conditions and pest changes brought forth by global warming.

Here we review the effects of climate change on crop cultivars alongside with these on weeds. Increases in marketable yield, mainly through increases in biomass, of cereals, particularly those that exhibit C3 photosynthetic pathway, range between 8-70%, these of row, cash and vegetable crops between 20-+144% and these of flowers between 6-35%. Nevertheless, the positive effects of elevated $CO_2$ on yield will most probably be affected by the availability of other resources such as water or nutrients. Temperature increases will decrease crop yields of temperature-sensitive crops such as maize, soybean, wheat, and cotton or specialty crops such as almonds, grapes, berries, citrus, or stone fruits at regional and local scale. Additionally crops like rice, which is expected to yield better under increased $CO_2$, will suffer serious yield losses under high temperatures. Significant crop yields reductions that occur under drought stress for tomato, soybean, maize, cotton are strongly demonstrated. Nevertheless, reviews on C4 photosynthesis response to water stress in interaction with $CO_2$ concentration revealed that elevated $CO_2$ concentration lessens the deleterious effect of drought on plant productivity. Weeds with C3 photosynthetic pathway are likely to respond more strongly than C4 types to $CO_2$ increases through biomass and leaf area increases. The positive response of C3 crops to elevated $CO_2$ may make C4 weeds less competitive for these crops whereas C3 weeds in C4 or C3 crops, particularly in tropical regions, could become a problem. Temperature increases will mainly affect the distribution of weeds, particularly C4 type, by expanding the geographical range they can be established. This will enhance further yield losses and will affect weed management systems negatively. In addition, the expansion of invasive weed species such as itchgrass, cogongrass and witchweed facilitated by temperature increases will increase the cost for their control. Under water- or nutrient shortage scenarios, an r-strategist with characteristics in the order S-C-R, such as Palmer amaranth, large crabgrass, johnsongrass and spurges will most probably prevail. It is becoming obvious that selection of cultivars that secure high yields under climate change but also by competing weeds successfully is of major importance. Traits related with a) increased root:shoot ratio, b) vernalization periods, c) maturity, d) regulation of node formation and/or internode distance, e) harvest index variations and f) allelopathy merit further investigation. The cumulative effects of selecting a suitable stress tolerator-competitor cultivar will be reflected in reductions of environmental pollution, lower production costs and sustainable food production. It is therefore imperative to expand research efforts to investigate how crop-weed interference under various abiotic stresses and cropping systems influences cultivar performance and subsequent yield outcome.

**Keywords**: stress tolerance; climate change; carbon dioxide; drought; temperature; weed competition; competitive ability; cultivar selection; integrated weed management

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## 1.0 Introduction

Climate change refers to long term changes in the state of the climate (IPCC, 2014). These changes are identifiable i.e. the mean or the variability of climate change components such as increase of temperature or elevated atmospheric $CO_2$ levels can be assessed by the application of appropriate analytical and statistical methods (IPCC, 2014). The release of greenhouse gases (carbon dioxide, methane, nitrous oxide) due to various anthropogenic activities is very likely to be one of the major causes of recent climatic change (Glover et al., 2008). Plausible climate change scenarios include higher atmospheric $CO_2$ concentrations, higher temperatures and changes in precipitation (Adams et al., 1998; Trenberth et al., 2007).

Climate change will impact many aspects of the human and natural world (IPCC 2007), but effects on agricultural production could be of particular significance (Cline, 1992). According to Cline (1992) estimates of annual damages in agriculture due to temperature increase, for example, will be more costly to US economy compared to those in other sectors and activities such as forestry, electricity, water availability or water pollution, air pollution, human mortality and morbidity, leisure activities, migration, human amenities and urban infrastructure. The multifaceted climate alterations necessitates the adaptation of crop plants to tolerate increased heat, extended drought periods (Figure 1a) (Gala Bijl and Fisher, 2011), or increased flooding in tropical places. Additionally, the expected changes in the distribution, abundance, and severity of pests and weeds (Bazzaz and Carlson, 1984; Ziska and Runion 2007; Ziska 2014) will affect cropping systems and pest control methods (Anonymous, 2008). Although climate changes compel agriculture to be adequately productive (Tokatlidis, 2013), its effects on agricultural production can be positive in some agricultural systems and regions and negative in others (Gregory et al., 2005; Obirih-Opareh and Adwoa Onumah, 2014).

To counteract the effects of climate change various adaptation strategies have been suggested. These, according to IPCC (2014), are the processes of adjustment to actual or expected climatic changes and its effects. In agricultural production systems adaptations seek to lessen or avoid damages caused by climate changes or exploit beneficial opportunities (IPCC, 2001; Adger et al., 2002). Farmers, throughout history, responded to changes in environment by adopting new crop cultivars and by adjusting their cultural practices (Gala Bijl and Fisher, 2011). At the farm level, these adaptations include alterations in planting and harvest dates, changes in cropping sequence, better management of water for irrigation, optimized use of fertilizers and adoption of various tillage practices (Adams et al., 1998). In addition, studies in Australia showed that crop responses to climate change are strongly cultivar-dependent (Wang et al., 1992). Asfaw and Lipper (2011) predicted that the farmers' primary response to climate change would be to seek and crop cultivars that are most adapted to highly variable, extreme climatic conditions and pest changes brought forth by global warming.

Weed interference, in addition to climate change, enhances the risk for further crop yield losses. Despite the advanced technological achievements for weed control, crop yields are suffering great losses due to weed competition (Figure 1b). Overall, weeds caused the greatest potential loss (34%), with animal pests and diseases being, usually, less important (losses of 18 and 16%) (Oerke, 2006). Competitiveness, adaptation, and stress tolerance are the characteristics by which weed species secure their survival in a variety of environmental conditions. Competitiveness, within the context of this paper, pertains to the ability of an organism (weed species in this case) to perform better in acquiring resources in relation to another organism (crop plants) within the same habitat. Adaptation is a change or a process of change by which an organism becomes better suited to a ‘new’ environment whereas tolerance is the ability of an organism to survive and reproduce under adverse environmental conditions. Weediness, which comprises traits that secure the survival and dispersal of weeds, even under severe environmental conditions, can be described through various morphological, phenological, or physiological characteristics. One of the main components of integrated weed management strategies for farmers is to grow crops able to offset the competitive ability of weeds. The utility of crops with weed-suppressive ability particularly in low input agricultural systems, or in situations when chemical weed control is not possible, can be proved valuable (Gibson et al., 2003; Benaragama et al., 2014). However, selection for weed-suppressive cultivars is difficult because this trait is a manifestation of the joint activity of many genes, controlling many traits. As reports have shown, a combination of characteristics, instead of a single trait, interact for enhanced weed- suppressive ability (Andrews et al., 2015). These traits are related to: a) crop morphological performance at early stages (i.e. rapid emergence, rapid root and shoot growth, early groundcover, early biomass accumulation, rapid leaf area development); b) crop growth characteristics (i.e. height, growth habit, tillering ability, leaf width, maturity date); c) crop physiological performance (i.e. ability for efficient water and nutrients uptake; and d) potential allelopathic properties (Korres and Froud-Williams, 2002; Korres, 2005; Mason and Spaner, 2006).

Climate change, in combination with an increasing world population, is predicted to escalate the global need for farmland, a resource that is already in high demand (Barrow et al., 2008) dwindling rapidly. The adoption of stress-tolerant cultivars that can withstand adverse climatic changes and produce high yields is an effective strategy against the unprecedented risks of climate change on crop productivity (Ciais et al, 2005) and the increasing demand for higher food production (Larson, 2013) particularly in low-input farming systems that are common in marginal areas (Darwin and Kennedy, 2000). Furthermore, stress-tolerant cultivars that exhibit attributes of increased suppressive ability against weeds would secure yield production even more either directly by dominating over weeds or indirectly by reducing crop management inputs (Korres and Froud-Willliams, 2002). To our knowledge, information that enables the evaluation of the relative strengths and weaknesses of both crops and weeds under various climate change scenarios is negligible. This paper aims to cover this gap and to discuss the benefits of selecting stress tolerant cultivar as a tool for integrated weed control under various climate change scenarios.

## 2.0 Effects of climate change on crops

### 2.1 Effects of elevated $CO_2$

#### *2.1.1 Effects of elevated $CO_2$ on crop physiological characteristics*

Increasing levels of atmospheric $CO_2$ due to various anthropogenic activities will directly influence photosynthesis, transpiration, and respiration, the main processes by which elevated $CO_2$ can be sensed directly by the plants and ecosystems (Drake et al., 1997). C3 and C4 plant types exhibit different responses to $CO_2$ enrichment. The current amount of $CO_2$ in the atmosphere is inadequate to saturate the ribulose 1, 5-biphosphate (RuBisCO) enzyme that drives photosynthesis in C3 plants (Taiz and Zeiger, 1991; Chijioke et al., 2011). Therefore future increases in $CO_2$ concentrations up to 57% by 2050 (Hulme, 1996), or even at higher levels (600-800 ppm) (Schmidhuber and Tubiello, 2007), will most probably favor C3 plant types (Table 1). In contrast C4 type plants are likely to respond less to elevated $CO_2$ levels as they possess an innate concentrating mechanism that increases $CO_2$ level at the site of RuBisCO to 2000 ppm.

Hence, predicted increases in atmospheric $CO_2$ concentrations, from a current ambient level of about 370 ppm, are less relevant to the photosynthetic capacity of C4 plants which, most probably, will respond only marginally (Poorter and Navas, 2003). The association of photosynthesis rate and intercellular $CO_2$ concentration was compared in soybean (C3) and maize (C4). Photosynthesis in soybean was stimulated by 39% under elevated $CO_2$ concentration but not in maize (Leakey et al., 2009).

*2.1.2. Effects of elevated $CO_2$ on crop yields*

Carbon dioxide is fundamental for plant production, and increases of atmospheric $CO_2$ concentrations have the potential to enhance the productivity of agro-ecosystems (Table 1) (Adams et al., 1998). Elevated $CO_2$ is expected to increase plant yield through root mass and leaf area increases (Table 1) and to alter plant chemical composition, hence the rate of nutrient cycling in soil (Campbell et al, 1997). Increases in marketable yield of cereals, particularly those that exhibit C3 photosynthetic pathway, range between 8-70%, these of row, cash and vegetable crops between 20-144% and these of flowers between 6-35%. The quality of agricultural products may be altered also by elevated $CO_2$. Nitrogen content, for example, in some non-nitrogen fixing plants grown at elevated $CO_2$, was found reduced (Ainsworth and Long, 2005; Erbs et al., 2010). These changes could affect the nutritional value, taste, and storage quality of some fruits and vegetables (Chijioke et al., 2011; Vermeulen et al., 2012).

### 2.2 Effects of temperature increases

*2.2.1 Effects of temperature increases on crop physiological characteristics*

Temperature increases result in altered phenology of leaf development, flowering, harvest and fruit production, decreased vernalisation period, and in asynchrony between flowering and pollinators (Baldocchi and Wong 2008). In addition, increased temperatures result in higher respirations rates, shorter seed formation periods, and lesser biomass production; hence, lower yields (Stone and Nicolas, 1995; Adams et al., 1998). Key stages of crop development, seasonal temperature incidents, day-night temperature fluctuations and geographical scale are the major parameters that should be taken under consideration when the effects of temperature on crop yields are evaluated. Only few days of extreme temperatures at the flowering stage can drastically reduce yield in many crops (Wheeler et al. 2000). Pre- and post-anthesis heat incidents at 35 $^{o}$C led to significant yield loss of barley, wheat, and triticale (Zheng et al., 2002; Porter and Semenov, 2005; Ugarte et al., 2007). Increases in spring temperatures have been shown to induce earlier spring flowering (Pope et al., 2013), reductions in pollen germination, flowering and ovule size with subsequent fruit yield declines due to smaller, deformed and fewer fruit production in perennial crops (Pope, 2012; DeCeault and Polito, 2008). Each crop species exhibits an optimal temperature for vegetative growth with growth decreasing as temperatures diverge from this optimum. Similarly, there is a range of temperatures within which a plant will set seeds and outside of which the plant will not be able to reproduce. Maize, for instance, will fail to reproduce at temperatures above 32 $^{o}$C and soybean above 38 $^{o}$C (Figure 2). Consequently, the trend in India toward more production of wheat, rice, and barley, and less production of maize and millets, is likely to accelerate, whereas in the USA, production might shift away from maize into soybean (C3) for forage (Parry, 1990). High temperatures (above 35 °C) in combination with high humidity and low wind speed caused a 4 °C-increase in rice panicle temperatures, resulting in floret sterility (Tian et al., 2010).

*2.2.2 Effects of temperature increases on crop yield*

Crop yields particularly these of temperature-sensitive crops such as maize, soybean, wheat, and cotton (Schlenker and Roberts, 2009), or specialty crops such as almonds, grapes, berries, citrus, or stone fruits (Lobell and Field, 2011; Lobell et al., 2006) will be decreased with temperature increases at regional and local scale (Bonfils, 2012; Lobell et al., 2006). Night temperature increases resulted in rice and wheat grain yield losses (Lobell et al., 2005; Peng et al., 2004; Mohammad et al., 2009). Thus, even a C3 crop like rice which is expected to yield better under increased $CO_2$, will suffer serious yield losses under high temperature. Since the majority of global rice is grown in tropical and semi-tropical regions, it is likely that higher temperatures would negatively affect its production in these areas due to an increase in floret sterility that would subsequently decrease yields (Prasad et al. 2006a, b). The detrimental effect of high temperature on rice yield will be exacerbated by increased $CO_2$ in the atmosphere.

## 2.3 Effects of water deficit

### *2.3.1 Effects of water deficit on crop physiological characteristics*

Physiological responses of plants to drought stress are complex and vary with plant species and the degree or time of the exposure to drought (Bodner et al, 2015; Evans et al., 1991). Under drought conditions, photosynthesis inhibition occurs because of stomata closure and reductions in the $CO_2$:$O_2$ ratio in leaves (Jason et al., 2004).

### *2.3.2 Effects of water deficit on crop yield*

Significant crop yields reductions occur under drought stress through dry weight accumulation reductions in all plant organs and shorter plant life cycles (Blum, 1996). Pace et al. (1999) recorded significantly fewer nodes, lower dry weights of stems and reduction in height and leaf area between water-stressed and well-watered cotton plants (Table 3). In addition, water deficit at flowering may limit the viability of pollen, the receptivity of its stigma, and seed development (Blum, 1996). Reduced yields, especially in rain-fed cropping systems, is the norm under drought conditions (Kramer, 1983), the severity of which may increase due to changing world climatic trends (Le Houerou, 1996). One possible scenario is that the irrigated wetland rice (13 Mha of cultivated land) in Asia may experience physical water scarcity by 2025, while the irrigated dry-season rice (22 Mha of cultivated land) may suffer economic water scarcity (human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands) (Tuong and Bouman, 2003). Deleterious effects of water deficit on crops such as tomato (Ragab et al., 2007), soybean (Sakthivelu et al., 2008; Hamayun et al., 2010), maize (Khodarahmpour, 2011) and many others is well known.

### 2.4 Interactive effects of climate change components on the physiology of crop plants and yield

In previous sections the effects of climate change components on crop plants were examined individually although environmental changes occur concurrently (Albert et al., 2011) with management practices (Tubiello and Ewert, 2002). For instance, crop yield response to elevated $CO_2$ levels is relatively greater in rain-fed than in irrigated crops, due to a combination of increased water-use efficiency (Table 4) and root water-uptake capacity (Tubiello and Ewert, 2002). In addition, the projected increases in atmospheric $CO_2$ concentration will increase crop growth and consequently nitrogen uptake by the crop, thus potentially will increase the need for fertilizer applications if production is to be maximized (Olesen and Bindi, 2002). Elevated $CO_2$ resulted in a sustained larger N pool in above-ground biomass of grasses during a 5-year study on long-term enhancement of N availability under $CO_2$ concentration increases, suggesting that more N was taken up each year from the soil under elevated $CO_2$ (Dijkstra et al., 2008). Also, increased soil moisture under elevated $CO_2$ supported higher rates of N mineralization, thereby reducing N constraints on plant growth. More of the mineralized N ended up in the above-ground biomass of needle-and-thread [*Hesperostipa comata* (Trin. & Rupr.) Barkworth] (C3) than in blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths] (C4) under elevated $CO_2$ (Dijkstra et al., 2008). Therefore is possible that C3 species exhibit a higher plant N acquisition and utilization under elevated $CO_2$ concentrations. Ghannoum (2009) reviewed the C4 photosynthesis response to water stress in interaction with $CO_2$ concentration and reported that elevated $CO_2$ concentration lessens the deleterious effect of drought on plant productivity. This is due to reduced stomatal conductance, $CO_2$ assimilation rate, and intercellular $CO_2$ levels (Ghannoun, 2009; Ripley et al., 2007) therefore, saturating $CO_2$ concentration keeps the photosynthetic capacity unchanged and limits reductions in plant productivity.

## 3.0 Effects of climate change on weeds

Compared with crops, weeds have more variable characteristics as they have not been subjected to the same degree of selection for specific favorable traits (e.g. lack of seed dormancy, uniform growth, high yields). Hence, weeds tend to exhibit greater potential capability to adapt to stress than crop plants. The high genetic diversity among weedy plants allow them to achieve a greater competitive fitness against crops as a consequence of climate change (Dukes and Mooney, 1999). The major categories under which climate change will affect weed populations include species abundance and richness, geographic range, and phenology (Anonymous, 2013; Curtis and Wang, 1998).

### 3.1 Effects of elevated $CO_2$

#### *3.1.1 Direct effects of elevated $CO_2$ on weeds*

There is an acknowledged consensus regarding the direct impact of increased $CO_2$ on plant physiology (Ziska, 2004). Many weeds respond positively to elevated $CO_2$ due to decreased stomatal conductance (Bunce, 1998) and subsequent improvements in water-use efficiency (Patterson et al., 1999; Ziska and Runion, 2006). C3 plant types are likely to respond more strongly than C4 plant types to $CO_2$ increases (Southworth et al., 2002; Ziska, 2004) (Figure 3) through biomass and leaf area increases (Walthall et al., 2012). Nonetheless, results from various studies indicate significant and wide variations in response to elevated $CO_2$ due to interactions with temperature, light, water, and nutrients. $CO_2$ enrichment enhanced the growth and biomass production of annual fescue [*Vulpia myuros* (L.) C.C. Gmel.] (C3 type), Santa Maria feverfew weed (*Parthenium hysterophorus* L.) (C3/C4 intermediate type), and green amaranth (*Amaranthus viridis* L.) (C4 type)(Scott et al., 2014; Naidu and Paroha, 2008). Other direct effects of elevated $CO_2$ is the production of excess pollen in ragweed (*Ambrosia artemisiifolia* L.) (Wayne et al., 2002) and the accelerated maturity rate in wild oat (*Avena fatua* L.) (Anonymous, 2008).

*3.1.2 Indirect effects of elevated $CO_2$ on weeds*

Weed reproductive capacity will most probably be enhanced by increased $CO_2$ (Patterson et al., 1999; Ziska and Runion, 2006). In case of the green amaranth, a 274 percent increase in flower production under elevated $CO_2$ ($550 \pm 30$ ppm) in controlled environmental conditions was reported by Naidu and Paroha (2008). Reproductive capacity is linked to resource capture (DeFelice et al., 1988; Benvenuti and Steffani, 1994; Bello et al., 1995) which is related to increased biomass and leaf area (Korres, 2005). Therefore, increases in biomass with elevated $CO_2$ levels will enhance weed reproductive output as these two traits are positively correlated (Korres and Froud-Williams, 2002; Korres et al., 2015). Hence, increases in reproductive output will result in increases of weed abundance. Disruptions of soil and native plant populations for urban or rural development, emissions that increase atmospheric $CO_2$ concentrations, and nitrogen deposition to the ground surface which enhance weed growth (Johnson and California Invasive Plant Council, 2013), and roadside activities which lead to the spread of weeds (Korres et al., 2015) will further enhance weed abundance. In addition, Ziska et al. (2004) observed that elevated $CO_2$ concentrations increased root biomass of Canada thistle (C3 plant type), suggesting that perennial weeds might be more difficult to control at these higher $CO_2$ levels.

*3.1.3. Effects of elevated $CO_2$ on crop-weed interference*

Some of the world's most troublesome weed species are C4 types and are found in C3 crops (Edwards and Huber, 1981). The positive response of C3 crops to increased $CO_2$ may make such weeds less competitive (Table 5). In contrast, C3 weeds in C4 or C3 crops, particularly in tropical regions, could become a problem (Table 5), although the final outcome will depend on other climate change components (Morison, 1989). Despite the fact that many weed species exhibiting a C4 photosynthetic pathway show less response to atmospheric $CO_2$ relative to C3 crops, in most agronomic situations, a mix of both C3 and C4 weeds occurs. As stated earlier increases in $CO_2$ concentrations will enhance C3 weed growth particularly for those species that reproduce by vegetative means (Ziska and George, 2004; Ziska, 2003). Consequently, the abundance of perennial weeds such as common couch [*Elytrigia repens* (L.) Desv. Ex. Nevski], heartshape pickerelweed [*Monocharia vaginalis* (Burm. F.) Presl], cosmopolitan bulrush [*Scirpus maritimus* L.], hedge bindweed [*Calystegia sepium* (L.) R. Br.], Canada thistle [*Cirsium arvense* (L.) Scop], perennial sowthistle [*Sonchus arvensis* L.], horsenettle [*Solanum carolinense* L.], most of them found in rice or soybean cropping systems, may increase, since elevated $CO_2$ stimulates greater rhizome and tuber growth (Chandrasena, 2009).

**3.2 Effects of temperature**

*3.2.1 Effects of temperature on weed physiological characteristics*

Soil temperature is the primary determinant of seed germination and survival particularly when soil freezes (Zimdahl, 2007). Various responses to temperature fluctuations have been reported for seed germination of weed species. Common chickweed (*Stellaria media* L.) survives well in cold climates (King, 1966), whereas some of the most troublesome weeds in soybean, maize, and cotton respond to temperature gradients to varying degrees (Ehleringer, 1983). Barnyardgrass (*Echinochloa* spp.) is a weed of warm regions that requires high temperatures for dry matter production and growth (Maun and Bennett, 1986). Similarly prickly sida (*Sida spinosa* L.) needs high temperatures for its development (Anonymous, 2001). The spatial distribution of johnsongrass [*Sorghum halepense* (L.) Pers.] in colder climates is restricted by its rhizome intolerance to temperatures below -3 $^{o}$C (Warwick and Black, 1983). Similarly, morningglories are frost intolerant (Halvorson and Guertin, 2003; Zia Ul-Haq et al., 2012) but their germination occurs over a wide range of temperatures (15-35 $^{o}$C) (Cole and Coats, 1973-cited in Halvorson and Guertin, 2003) with optimum germination temperature at 24 $^{o}$C (Crowley and Buchanan, 1980-cited in Halvorson and Guertin, 2003). In addition, Ziska et al. (2007) reported 88% increase in biomass and 68% increase in leaf area of itchgrass [*Rottboelliia cochinchinensis* (Lour.) W.D. Clayton] in response to a 3 $^{o}$C-increase in temperature.

*3.2.2 Effects of temperature on weed distribution*

The geographical range of many weed species is largely determined by temperature and it has long been recognized that temperature determines successful colonization of new environments by weedy species (Woodward and Williams, 1987). Warming will affect the growth, reproduction and distribution of weeds. Increased temperatures could, for example, alter the latitudinal distinction between Midwest and Midsouth regions within the USA, altering the weed geographical limitations. The greater soybean and maize losses experienced in the Midsouth are associated with a number of very aggressive weed species of tropical or sub-tropical environments such as prickly sida and johnsongrass (Osunsami, 2009; Riar et al., 2013).

Obviously, increased temperatures will facilitate the spread of these species into other areas of the Midwest with subsequent effects on soybean and maize production (Walthall et al., 2012). Temperature increases are likely to be particularly important in affecting the relative plant growth of C3 and C4 plants, potentially favouring C4 weeds (Dukes and Mooney, 1999), such as smutgrass (*Sporobolus indicus* L. R. Br.). This again could provide suitable conditions for more robust growth of some species, which are currently limited by low temperatures, whereas the distribution of some tropical and sub-tropical C4 species could shift northwards (Ziska and Runion, 2006; Chandrasena, 2009), thus exposing temperate-zone agriculture to previously unknown aggressive colonizers.

In addition, Ziska et al. (2007) stated that an expansion of invasive weed species such as itchgrass, cogongrass [*Imperata cylindrical* (L.) P. Beauv.] and witchweed [*Striga asiatica* (L.) Kuntze] will be facilitated by temperature increases. They also reported an increase in biomass and leaf area of itchgrass by 88 and 68% respectively in response to a 3 $^{o}$C-increase. On the contrary, additional warming could restrict the southern range of other cooler-climate invasive weeds such as wild proso millet (*Panicum miliaceum* L.) or Canada thistle (Ziska and Runion, 2007).

## 3.3 Effects of water deficit

### *3.3.1 Effects of drought on weed physiological responses*

Under more frequent and severe drought stress events due to climate change, the competitive balance would shift in favor of deep-rooted plants (Stratonovitch et al., 2012). Early emerging species, such as the shallow-rooted Sandberg’s bluegrass (*Poa sandbergii* Vasey), which uses the resources that are available in the upper soil profile early in the growing season and during periods of light precipitation, will be suppressed (Daudenmire, 1970 cited in Sheley et al., 1996).

In addition, dry soil conditions prolong the longevity of weed seeds due to unfavorable conditions for seed predators (Storrie and Cook 2007) and unfavorable conditions for germination. Weed seeds such as black bindweed (*Polygonum cilinode* Michx.) can last up to seven years in the soil under dry conditions (Storrie and Cook, 2007). A summary of the potential impacts of drought stress on some of the most important Australian weeds are shown in Table 6 where a trend of establishment in higher latitudes is expected (Anonymous, 2008).

*3.3.2 Weed adaptation strategies under water deficit and other unfavorable conditions*

As reported by Wiese and Vandiner (1970), species with greatest growth under high soil moisture conditions will be the most adversely affected by the combination of competition and water shortage. On the contrary, the more competitive species under semi-drought conditions are likely to be those that produce little growth in moist soils. Based on the competitive exclusion principle, the species that uses a resource more efficiently will eventually, either wholly or partially, displace the other species. This opportunistic behavior characterizes the r-strategists, those with short life cycle and high energy investments into reproduction and dispersability, as opposed to K-strategists (Sheley et al., 1996; Hardin, 1960). Grime (1979) extended the r- and K-classification strategies into stress tolerators (S), competitors (C), ruderals (R) or combinations of the above strategies. Under high stress intensity that can limit plant growth, as in the case of water or nutrient shortage, stress tolerators (S) can perform adequately. Based on the ability of adjacent organisms to exploit the same resource competitors (C) will perform best whereas ruderals (R) can withstand physical damages. Most weeds of annual agricultural systems exhibit ruderal-competitive characteristics, whereas most weeds of rangeland and forest ecosystems exhibit stress tolerance-competitive characteristics. Typically, succession is evolved from ruderal to competitive and finally to stress tolerator species (Korres, 2005). Hence, under water- or nutrient shortage scenarios, an r-strategist with characteristics in the order S-C-R, will most probably prevail. In a recent weed survey (Korres et al., 2015), the preference of Palmer amaranth, large crabgrass (*Digitaria sanguinalis* L. Scop.), johnsongrass, and spurges (*Euphorbia* spp.) for disturbed habitats was reported. In the same survey, giant ragweed (*Ambrosia trifida* L.), yellow nutsedge (*Cyperus esculentus* L.), barnyardgrass, and hemp sesbania [*Sesbania herbacea* (Mill.) McVaFugh] exhibited a strong preference for moist habitats. Obviously, the former group of weeds is assured of a greater probability for survival under water or nutrient stress conditions in comparison to the latter.

### 3.4 Interactive effects of climate change components on weed performance and consequences on weed-crop competition

The influence of climate change on simple competitive outcomes will be difficult to predict based simply on a single model, as interactions between the various climate change scenarios are likely to concur and will affect the outcome of the crop-weed competition (Alberto et al., 1996). The growth of a tropical weed is strongly stimulated by relatively small changes in air temperature (Patterson et al., 1984), but the potential synergistic effects of rising $CO_2$ on these weeds relative to tropical crops is unknown. It is believed that increased $CO_2$ and temperature can negatively impact plant growth. Scott et al. (2014), for example, reported that increases in both parameters negatively impacted plant growth rates in grassland ecosystems. The effects of elevated $CO_2$ levels on crops and weeds will alter the weed-crop competitive interactions, sometimes for the benefit of the crop and sometimes for the weeds. Consequently, the control of weeds will also likely be affected by these changes (Patterson, 1995; Coakley et al., 1999). Reduction in transpiration and changes in leaf anatomy and leaf surface characteristics, or greater root to shoot ratio caused by elevated $CO_2$, could also affect herbicide uptake, thus reducing herbicide efficiency (Patterson et al., 1999; Olesen and Bindi, 2002; Poorter and Navas, 2003; Dukes et al., 2009). This was confirmed by various studies in which increased $CO_2$ concentration has affected the efficacy of glyphosate on both C3 and C4 weed photosynthetic types (Ziska et al., 2004; Manea et al., 2011; Ziska et al., 1999) (Table 7). This response to carbon dioxide in combination with the evolution of glyphosate resistance by many weed species (Heap, 2015), will affect weed control schemes significantly. Controlling weeds currently costs the United States, more than $11 billion a year, with the majority spent on herbicides, hence both herbicide use and costs are likely to increase as temperatures and carbon dioxide levels rise (Karl et al., 2009).

Additionally, little attention has been focused on the interactions between nutrient availability or drought with rising $CO_2$, on weed-crop competition. According to Newton et al. (1996) the proportion of weed biomass increased with elevated $CO_2$ equally in wet and dry treatments in pasture mixture. In another study, reduced weed competition was observed when tomato (C3 crop) and redroot pigweed (C4 weed) were grown under well-watered conditions, but when drought and high $CO_2$ occurred synchronously, redroot pigweed performed better (Valerio et al., 2011). Under extreme nutrient limitations, stimulation of biomass with additional $CO_2$ may be minimal. However, under moderate nutrient limitations, more indicative of agroecosystems, the increase in biomass may be reduced but still occurs (Seneweera et al., 1994). Under a competitive environment between rice (C3 crop type) and barnyardgrass (C4 weed type), the proportion of rice biomass increased relative to barnyardgrass with a 200 ppm increase in atmospheric $CO_2$, but only when soil nitrogen was adequate. If nitrogen was limited in an enriched $CO_2$ environment, the competitive ability of rice relative to barnyardgrass was reduced, possibly due to reductions in tiller formation (Zhu et al., 2008). Elevated $CO_2$ can mitigate some of the adverse effects of increased temperature and drought and also regulate the adaptive mechanism of black knapweed (*Centaurea nigra* L.) (Qaderi et al., 2013). The effects of drought are likely to vary widely among crops and weeds. In maize, drought has been found to both decrease interference from naturally occurring weed flora dominated by foxtail species (*Setaria* spp.) (McGiffen et al., 1997), and increase the competitive ability of johnsongrass (Leguizamon, 2011). Drought and high temperatures favor the competitive ability of C4 weeds over C3 crops (Fuhrer, 2003), an advantage which will most probably diminish or possibly be reversed under increased $CO_2$ concentrations (Bazzaz and Carlson, 1984; Carter and Peterson, 1983). Spatial-based effects of temperature increases and prolonged drought periods on weeds have also been anticipated. More particularly, long drought periods interspersed with occasional very wet years will enhance weed invasion because established vegetation, both native and crops, will be weakened, leaving some areas open to invasion (Chandrasena, 2009). In general, wetter and milder winters are likely to increase the survival of some winter annual weeds, whereas warmer summers and longer growing seasons may permit thermophile summer annuals to grow in regions further north (Peters et al., 2014). Alterations in temperature and nutrients supply can reduce photosynthetic rate of Palmer amaranth. The combination of temperature between 36-46 $^{o}$C with resource supply constraints may restrict the potential distribution range of Palmer amaranth (Ehleringer, 1983; Ward et al., 2013).

## 4.0 Cultivar selection against weeds and traits that confer competitiveness

Crop ability to suppress weeds can be considered in two ways, namely a) an ability to tolerate weed competition which can be measured by the ability of the crop to maintain high yields under weedy conditions, and b) the ability of the crop to suppress the growth of weeds, usually determined by comparing different biological characteristics in mixtures with that in pure stands, known as weed suppression ability or competitive ability (Callaway, 1992; Korres, 2004 Andrews et al., 2015). However, there is a confusion between cultivar tolerance to weed competition and cultivar weed suppressive ability (Olesen et al., 2004). Furthermore, crop tolerance to weed competition varies widely over seasons and locations (Cousens and Mokhtari, 1998; Olesen et al., 2004). Thus, weed suppression criterion has been emphasized here for the selection of suitable cultivars against weeds under various climate change scenarios.

*4.1 Cultivar phenotypic characteristics and weed suppression*

Unlike breeding for diseases and pest resistance, little research has been done on breeding crop cultivars which are more competitive to weeds. Certain crop cultivars are known to be better competitors with weeds than others (Callaway, 1992). For example, white bean (*Phaseolus vulgaris* L.) cultivars differ in their ability to compete with weeds (Malik et al., 1993). Certain tomato cultivars (*Lycopersicon esculentum* L.) have considerable tolerance to dodder (*Cuscuta* spp.), a severe parasitic weed in many parts of the world (Goldwasser et al., 2001). Cultivars of small grain cereals with certain characteristics such as short stature, earlier maturity, better winter hardiness or early season growth have shown differential competitive abilities when grown in mixtures compared to monocultures (Juskiw et al., 2000). As stated by various authors breeding crop cultivars with an enhanced ability to suppress weeds would be a sustainable contribution to improved weed management in many crops (Didon and Bostrom, 2003; Lemerle et al., 2001; Paolini et al., 1998; Vollmann et al., 2010). Therefore, cultivar selection with traits that enhance its ability to suppress weeds such as these mentioned above could be explored under various climate change scenarios. Additionally, the belowground traits such as root length density, root elongation rate, total root length, and root spatial distribution are important factors for attributing competition effect (Gealy et al. 2013a; Fargione & Tilman, 2006; Stevanato et al., 2011). The greater ability to extract water from dry soil may affect or even determine the competitive ability of a cultivar (Song et al, 2010). Reports have shown that under weed competition the root:shoot ratio of the crop and weeds was reduced (Kasperbauer and Karlen, 1994; Thomas and Alison, 1975; Stone et al, 1998), particularly of the less competitive species, although soil water content was not a limiting factor (Thomas and Alison, 1975; Rajcan and Swanton, 2001). However, as stated by Rajcan and Swanton (2001), competition for water should be viewed as an outcome of the interaction between both soil-plant-atmosphere and the crop-weed systems, rather than simply as a shortage of available water.

*4.2 Implications for allelopathic properties*

Weed suppression can vary with management factors such as planting method, seeding density, flood depth, and nitrogen fertilization whereas in some cases, activated charcoal has reduced the inhibition of weeds in soils, implicating allelopathic activity as a possible contributing factor (Kong et al., 2008; Kong et al., 2011). Rondo, for example, a rice cultivar grown in a commercial organic rice production operation in Texas, USA that combines a high yield potential and a weed suppression ability is considered as a potential cultivar with allelopathic properties (Gealy and Yan 2012). Bertholdsson (2010) bred spring wheat for improved allelopathic potential by conventional breeding. The material used originated from a cross between a Swedish cultivar with low allelopathic activity and a Tunisian cultivar with high allelopathic activity.

Therefore, research efforts have focused on combining allelopathic activity with other weed-suppressive traits in small grains such a rice (Figure 3). Breeders in Asia showed that allelopathic traits in rice can be quantitatively inherited (Chen et al., 2008) and weed-suppressive cultivars have now been developed in that region (Kong et al., 2011; Ma et al., 2006; Pheng et al., 2009a, 2009b). Similar progress has been reported in the USA (Gealy et al., 2013b). Breeding efforts with other small grains in Europe, using a dual screening approach of seedling bioassays for allelopathic potential coupled with field evaluations for general weed suppression, have resulted in germplasm with improved weed suppression or tolerance (Bertholdsson 2005, 2007, 2010). It has been reported that early season crop biomass and allelopathic potential were key traits for improved weed suppression by the crop (Bertholdsson, 2011; Bertholdsson et al., 2012). Worthington and Reberg-Horton (2013) have reviewed important breeding issues for small grains associated with optimization of weed-competitive ability and allelopathic traits. Rice traits such as rapid seedling growth, leaf area, and tiller production, and high yield potential have improved weed suppression and minimized crop yield loss (Gealy and Moldenhauer, 2012; Gealy and Yan, 2012; Gibson et al., 2003; Pérez de Vida et al., 2006). Zhao et al. (2006) successfully selected cultivars for weed-suppressive traits such as yield, early vigor, and height under weed-free conditions to identify weed- competitive cultivars.

## 5.0 Traits for developing an ideotype S-C cultivar

The use of tolerant cultivars to a wide range of climatic fluctuations as adaptive tool is widely spread (Matthews et al., 1994). In Australia, for example, the use of late maturing cultivars secures high yield outcomes that could be otherwise affected by inconsistent climatic conditions (Connor and Wang, 1993). A similar strategy, at crop level, is used in Canada and China, where the diversification of crops counteracts the climatic fluctuations (Hulme et al., 1992; Cohen et al., 1992).

### 5.1 *Cultivars with deep root system*

Adapting a cultivar with a deep root system, particularly in areas which experiencing prolonged dry periods can be a useful tool (Bodner et al., 2015). Newly introduced wheat cultivars can better exploit water and nutrients (Korres et al., 2008) mainly due to their greater ability to maintain water uptake and consequently to survive longer in dry soils (Song et al., 2009). Sorghum, for example, seems an attractive option for dry lands where crops frequently encounter drought stress compared to maize. Sorghum has deep root system, high root density, cuticle and epicuticular deposition in leaves, and efficient stomata function under water stress (Assefa et al., 2010; Starggenborg et al., 2008; Schittenhelm and Schroetterm, 2014). Traits related to competitiveness for water and nutrients that could affect the weed suppressive ability of the crop include root density, root length, water uptake rate and root surface area (Aarssen, 1989; Callaway, 1992; Mohler, 2001). In the long-term, breeding drought-tolerant cultivars might be advantageous for weed suppression as well as a means to cope with climatic changes in areas with prolonged summer dry periods (Bodner et al., 2015). Acquiring and utilizing water and nutrients more adequately compared to weeds due to their extensive root system, for example, will enable to crop cultivars to maintain growth even under drought conditions. Cultivars with high early vigor and earlier maturity can be used as an effective adaptation strategy for areas with semi-arid continental climates in temperate zones where more frequent generative droughts are forecasted (Gouache et al., 2012; Bodner et al., 2015). Genetic manipulation using molecular breeding has resulted in commercialization of drought-resistant crops such as the maize-DroughtGrade™ (Monsanto, St. Louis, USA) that is already used extensively in the US (Waltz, 2014). Differences in resistance to drought are known to exist within genotypes of plant species (Grzesiak et al., 2012) e.g. in, wheat (Winter et al., 1988; Paknejad et al., 2007), rapeseed (Richards & Thurling, 1978), oat (Larsson and Gorny, 1988), and triticale (Royo et al., 2000; Grzesiak et al., 2012). Nevertheless, drought tolerance does not necessarily provide competitive advantages to the crop. As reported by Cerqueira et al. (2013), two drought-tolerant upland rice cultivars were affected by the competition of shrubby false buttonweed (*Spermacoce verticillata*

L.) regardless of water conditions (presence and absence). In addition, as reported by Chauhan and Abugho (2013), rain-fed rice plants under weed competition with spiny amaranth (*Amaranthus spinosus* L.) and Chinese sprangletop [*Leptochloa chinensis* (L.) Nees] (C4 types) did not survive under limited water conditions. On the contrary both weed species, survived and produced a significant number of tillers and leaves.

5.2 *Harvest index and dry mater components*

To promote adaptation to high temperatures, plant breeders have suggested phenotypic traits related to heat tolerance during flowering, high harvest index, small leaves, and reduced leaf area per unit of ground area (Walthall et al., 2012). Differences between winter wheat cultivars in harvest index at high temperatures imply that heat-tolerant cultivars maintain higher grain development, compared to more temperature-sensitive cultivars (Wardlaw and Moncur, 1995). Lower harvest indices are an indication of injudicious investment of assimilates, a result of favoring biomass production over commercial yield (Hay and Walker, 1992). Therefore, genotypes with high harvest indices are expected to be weak competitors because of the relative fewer resources allocated for stem and leaf expansion (Kawano and Jennings, 1983), traits that confer competitiveness. Mann (1980) stated that it might be possible to obtain improvements in harvest index and therefore yield, suggesting further reductions in straw length and maintenance of above ground biomass. Korres (2000) investigating winter wheat cultivar characteristics for increased competitive ability, found a negative relationship between number of leaf area/$m^2$ and infertile tillers/$m^2$. Questions that merit further thought are related to the manipulation of leaf area and infertile tiller production. If the production of infertile tillers could be manipulated, would this result in leaf area investments? Would increases in leaf area, hence interception of photosynthetic active radiation, in response to increased day length as the crop enters reproductive development cause higher yield production and enhance competitive ability? Would leaf area duration be affected and what would be the consequences for grain yield? However, specific leaf area, a characteristic which is positively correlated with relative growth rate, is usually reduced by elevated $CO_2$ thereby counteracting the positive response of photosynthesis (Bruhn et al., 2001).

5.3 *Late maturing cultivars*

Late-maturing soybean cultivars (group IV) depressed weed seed production and seed weight of both pitted morningglory (*Ipomoea lacunosa* L.) and hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. ex A.W. Hill] presumably through increased crop competitiveness (Bennet and Shaw, 2000) due to their ability to maintain vegetative growth longer (Nordby et al., 2002). Nevertheless, Rosenzweig and Tubiello (2007) suggested that under warmer climates, crops would tend to mature faster, resulting in less time available for carbohydrate accumulation and grain production. Responses to specific adaptation strategies for given cropping systems can still vary considerably, as a function of location and climate change scenario. Adapting longer-maturing cultivars, in a winter cereal production system requires enough precipitation over an extended growing season to sustain grain filling. If both warmer and drier conditions prevail, such an adaptation strategy is not applicable. On the contrary, the adaptation of fast growing species (i.e. those with high sink strength, hence positive response of photosynthesis) has the advantage of better competition for resources thus faster adaptation to a changed climate.

5.4 *Nutrients uptake and utilization*

Nutrient utilization, mainly nitrogen, is an important factor for cultivar selection as an adaptive strategy, but also as a crop competitiveness tools under various climate change scenarios. There is a general agreement that crop cultivars, particularly of cereals, can differ in their responsiveness to nitrogen (Gent and Kiyomoto, 1998; Duan et al., 2007; Benin et al., 2012) possibly due to greater sink capacity, hence better nitrogen utilization or more extensive root systems (Lupton et al., 1974; Foulkes et al., 1994). Crop biomass is a component of two processes namely the amount of accumulated intercepted radiation and radiation use efficiency (Monteith, 1977; Gallagher and Biscoe, 1978). Foulkes et al. (1994) stated that maximum growth depends on the acquisition of sufficient nitrogen to form a canopy of sufficient size to intercept the majority of the incident radiation when adequate moisture to balance evaporation from the canopy is provided. One of the main traits conferring resistance to drought in winter wheat is the flowering date (Foulkes et al., 1997). More particularly, cultivars with early flowering are less prone to drought effects due to shorter life cycle they exhibit. Susceptible cultivars to dry conditions, especially towards the end to the growing season, uptake and utilize lower nitrogen. Hence, cultivars with efficient N uptake and utilization that exhibit drought resistance characteristics can be used for weed suppression and also as adaptive tools in less fertile or dry soils.

5.5 *Heat tolerance-Improvements and expectations*

Improvements of heat-stress tolerant germplasm lines have resulted in the development of the Hoveyzeh rice cultivar from Khuzestan delta in south Iran which attains spikelet fertility at average day temperatures of 45 ºC (Jennings et al., 1979). Despite the impressive achievements by plant breeding programs, efforts to generate heat-tolerant crops have not been very successful. This is mainly because abiotic stress-tolerance in plants is quantitatively inherited and it is found to be controlled by multiple genes/quantitative trait loci (Blum et al., 1988). Advances in agricultural biotechnology have been successful in developing heat-tolerance transgenically under controlled conditions (Grover et al., 2013).

5.6 A *synthesis*

Breeding objectives should be re-orientated towards a selection of traditional × modern crop characteristics that will result in increased weed suppressive ability (Dingkuhn et al., 2010), an ability to thrive in harsh environments and high yielding potential (Jones et al., 1997; Johnson et al., 1998). Hybrids of *Oryza glaberrima* × *Oryza sativa* share common parental characteristics such as weed competitiveness, ability to grow under stressful conditions without jeopardizing their yield (Jones et al., 1997; Johnson et al., 1998).

Priority should be focused on crop traits suitable for climate change scenarios for several reasons. This is true considering the detrimental effects of increased temperature or extended drought periods on crop yields, for example, in combination with the enhanced plasticity and adaptation ability the weed species respond to various environment changes. If an appropriate trait for climate change adaptation favors the weed suppressive ability of the crop plant then its selection should be prioritized. The following Table (Table 8), in an attempt to facilitate the selection process, summarizes the major responses of both crop plants and weeds under various scenarios of climate change.

As mentioned earlier, increased temperatures will reduce vernalization (i.e. the promotion of flowering in response to a prolonged exposure to low temperatures) requirements for both crops and weeds, particularly grasses. This in turn will shorten the vegetative period due to early reproductive induction (Chauvel et al., 2002), at the vegetative points, of the apex (Chouard, 1960; Chauvel et al., 2002) which will result in biomass reductions for both crop plants and weeds and consequent yield reductions. As it was stated earlier increases in biomass production or its components e.g. leaf area, tillers, stem weight etc. are positively related to increased competitiveness for both crop plants and weeds as in the case of cereals, particularly winter wheat, and blackgrass [*Alopecurus myosuroides* Huds.] (Chauvel et al., 2002).

- Cultivars that retain appropriate vernalization periods under increased temperatures, hence maintaining vegetative growth stages, can preserve yield production but also to exhibit suppressive ability against weeds.
- The development of tolerant cultivars to drought with increased root:shoot ratio will result in enhanced water and nutrient uptake, unaffected growth rates and biomass production, hence improved weed suppressing ability.
- Traits related with the maturity of cultivars is another option that merits further consideration for developing cultivars tolerant to drought and enhanced suppressive ability against weeds.
- Traits associated with the regulation of node formation and/or internode distance, particularly under drought stress conditions, can be used for developing high yielding and competitive cultivars against weeds.
- Traits or plant attributes related with harvest index variations such as these of infertile tillers and leaf area as mentioned above merit further investigation since they can influence both yield production through increased utilization of resources (i.e. PAR) and weed suppressive ability (e.g. shading).
- Cultivars that exhibit allelophathic attributes should be prioritized in breeding programs.
- **7.0. Conclusions**

Climate change is predicted to affect agricultural production in many ways. Climate change is likely to affect the growth of both crops and weeds, sometimes benefiting the crop sometimes the weeds. Crop yield in many areas will decrease due to increased temperatures or extended drought periods whereas weed competition, despite the technological advances, will increase further crop yield reductions. A dual adaptive approach is needed not only to counteract the negative effects of climate change but also to enhance crop competitiveness against weeds. As it has been shown in this paper cultivar selection serves this adaptive approach adequately. Cultivars with C3 photosynthetic pathway are more suitable for adaptation to elevated $CO_2$ but also to compete with weeds, particularly those with C4 photosynthetic pathway. In addition, cultivars with mechanisms to resist drought through increases in root:shoor ratio will gain a significant advantage under dry conditions in marginal areas. The potential of these cultivars for weed suppression will more likely enhance, due to their ability to acquire water and nutrients effectively. However, increased temperatures, accompanied by extended drought periods, favour the selection of cultivars with longer maturity period which have also proved to be highly competitive by maintaining longer vegetative growth. Cultivars with allelopathic abilities should be used in integrated weed management systems since they have shown great potential for high yield production but also increased weed suppressing ability. This paper investigates the complex interactions between crops and weeds under various climate change scenarios aiming to facilitate decision -making processes towards sustainable crop production systems. Developing cultivars to tolerate climate changes such as drought, temperature increases or nutrient shortage can reduce fertilizer and irrigation inputs considerably. The incorporation of cultivars with enhanced weed suppression ability into the system can reduce herbicide inputs substantially (Callaway, 1992; Gealy et al., 2014; Gealy et al., 2003; Korres et al., 2008; Travlos, 2012). This is even more demanding considering the increase of weed herbicide resistance evolution (Heap, 2015). The cumulative effects from selecting a suitable S-C cultivar will be reflected in reductions of environmental pollution, lower production costs and sustainable food production. It is therefore imperative to expand research efforts to investigate how crop-weed interference under various abiotic stresses and cropping systems influences cultivar performance and subsequent yield outcome. This information could be incorporated into breeding programs for improving cultivars performance under abiotic (climate change) and biotic (weed competition) stresses without compromising final yield.

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**Table 1**. Response of C3 and C4 weeds and crops to doubled atmospheric $CO_2$ levels in relation to biomass and leaf area production for both crop plants and weed species with C3 and C4 photosynthetic pathway

| C3 species | Biomass | Leaf area | C4 species | Biomass | Leaf area |
|---|---|---|---|---|---|
| Range of response (× growth at ambient $CO_2$ concentrations) | | | | | |
| *Abutilon theophrastii* | 1-1.52 | 0.87-1.17 | *Amaranthus retroflexus* | 0.9-1.41 | 0.94-1.25 |
| *Bromus mollis* | 1.37 | 1.04 | Andropogon virginicus | 0.8-1.17 | 0.88-1.29 |
| *Bromus tectorum* | 1.54 | 1.46 | *Cyperus rotundus* | 1.02 | 0.92 |
| *Cassia obtusifolia* | 1.4-1.6 | 1.1-1.34 | *Digitaria ciliaris* | 1.06-1.6 | 1.04-1.66 |
| *Chenopodium album* | 1-1.6 | 1.22 | *Echinochloa crus-galli* | 0.95-1.6 | 0.98-1.77 |
| *Datura stramonium* | 1.7-2.72 | 1.46 | *Eleusine indica* | 1.02-1.2 | 0.95-1.77 |
| *Elytrigia repens* | 1.64 | 1.3 | *Paspalum plicatum* | 1.08 | 1.02 |
| *Phalaris aquatic* | 1.43 | 1.31 | *Rottboellia cochinchinensis* | 1.21 | 1.13 |
| *Plantago lanceolata* | 1-1.33 | 1.33 | *Setaria faberii* | 0.93-1.35 | 1-1.4 |
| *Rumex crispus* | 1.18 | 0.96 | *Sorghum halepense* | 0.56-1.1 | 0.99-1.3 |
| Range of response (% increase) | | | | | |
| *Triticum aestivum* | 17-31 | | *Zea mays* | 3.7-9 | |
| *Hordeum vulgare* | 30 | | *Sorghum bicolor* | 9 | |
| *Glysine max* | 39 | | | | |
| *Gossypium hirsutum* | 84 | | | | |
| *Ipomoea batatas* | 59-111 | | | | |

Adopted from Chandrasena (2009); Patterson (1985); Streck (2005).

**Table 2**. Effects of doubling $CO_2$ concentration on marketable yield* of major cereal, row, cash, vegetable crops and flowers.

| Crop | Marketable yield (% increase) |
|---|---|
| Maize** | 3.7-29 |
| Sorghum** | 6 |
| Wheat** | 8-35 |
| Barley** | 70 |
| Rice** | 25 |
| Soybean*** | 22-45 |
| Tobacco*** | 42 |
| Potato*** | 51 |
| Tomato*** | 20-26 |
| Lettuce*** | 35-44 |
| Cucumber*** | 30 |
| Sunflower*** | 144 |
| Chrysanthemum**** | 6 |
| Cyclamen**** | 35 |
| Rose**** | 8-27 |

Adopted from Streck (2005).

*Values shown in this Table were obtained by the compilation and analysis of the results of more than 770 reports about the effects of $CO_2$ enrichment on the economic yield of 24 agricultural crops and 14 other species; **cereals crops, *** row, cash and vegetables; ****flowers

**Table 3.** Plant height, stem and leaf dry weight, leaf area, and node number in drought-stressed and well-watered control cotton plants at the end of the drought (49 days after planting).

| | Treatment | |
|---|---|---|
| Plant part | Drought* | Control |
| Plant height | 20.0 | 27.9 |
| Stem dry weight (g) | 1.13 | 1.39 |
| Leaf dry weight (g) | 1.41 | 2.16 |
| Leaf area ($cm^2$) | 56 | 153 |
| Node number | 7.8 | 9.4 |

The drought treatment was imposed by withholding water for 13 d. *Means in a row are significantly different at the 0.05 probability level (based on Pace et al., 1999).

**Table 4**. Seasonal water use efficiency (g DM/kg water) under various water regimes and ambient and double $CO_2$ concentrations in various crop species

| | Ambient $CO_2$ | Double $CO_2$ | Ratio |
|---|---|---|---|
| Sorghum | 3.08 | 4.13 | 1.34 |
| Wheat (well watered) | 5.1 | 6.3 | 1.23 |
| Wheat (water shortage) | 6.2 | 8.9 | 1.43 |
| Wheat | 2.62 | 3.45 | 1.31 |
| Wheat (well watered) | 1.58 | 2.14 | 1.35* |
| Wheat (water shortage) | 1.27 | 1.86 | 1.46* |
| Faba beans | 4.91 | 7.82 | 1.59 |
| Water hyacinth | 1.4 | 2.6 | 1.85 |

Adopted from Morison 1993; *grain only

**Table 5**. Response of crop and weed species grown under competition as a function of high $CO_2$ concentration

| C4 weed vs. C3 crops | High $CO_2$ favours | Environment |
|---|---|---|
| *Sorghum halepense* vs. *Festuca pratensis* | Crop | Greenhouse |
| *Sorghum halepense* vs. *Glysine max* | Crop | Growth chamber |
| *Amaranthus retroflexus vs. Glysine max* | Crop | Field |
| *Echinochloa glabrescens* vs *Oryza sativa* | Crop | Greenhouse |
| *Paspalum dilatatum* vs. various grasses | Crop | Growth chamber |
| Various grasses vs. *Medicago sativa* | Crop | Field |
| C3 weed vs. C3 crops | | |
| *Chenopodium album* vs. *Beta vulgaris* | Crop | Growth chamber |
| *Taraxacum officinale* vs. *Medicago sativa* | Weed | Field |
| *Plantago lanceolata* vs. pasture | Weed | Growth chamber |
| *Taraxacum* and *Plantago* vs. pasture | Weed | Field |
| *Cirsium arvensis* vs. *Glysine max* | Weed | Field |
| *Chenopodium album* vs. *Glysine max* | Weed | Field |
| C4 weed vs. C4 crop | | |
| *Amaranthus retroflexus* vs. *Shorghum bicolor* | Weed | Field |

| | | |
|---|---|---|
| C3 weeds vs. C4 crops | | |
| *Xanthium strumarium* vs. *Sorghum bicolor* | Weed | Greenhouse |
| *Abutilon theophrasti* vs. *Sorghum bicolor* | Weed | Field |

Based on Bunce and Ziska (2000), Walthall et al. (2012).

**Table 6.** Potential effects of drought on Australian agricultural weeds

| Weed | Impact |
|---|---|
| Blackberry (*Rubus fruticosus* L.) | Expected to retreat to higher altitudes due to its sensitivity to higher temperatures and drought |
| Chilean needle grass [*Nassella neesiana* (Trin. & Rupr.) Barkworth)] | Expected to increase its range because its increased invasiveness ability (long-lived, seed dispersed by wind and water) and drought tolerance |
| Gorse (*Ulex europaeus* L.) | Establishment into high-rainfall zones due to its sensitivity to drought |
| Lantana (*Lantana camara* L.) | Establishment into high-rainfall zones |

Adopted from Anonymous (2008)

**Table 7**. Effects of increased $CO_2$ concentration on glyphosate efficacy for various weed species with different photosynthetic pathways

| Common name | Latin name | P/S pathway* | Efficacy change |
|---|---|---|---|
| Canada thistle | *Cirsium arvense* (L.) Scop | C3 | Reduced |
| Dallisgrass | *Paspalum dilatatum* Poir. | C4 | Reduced |
| Lambsquarters | *Chenopodium album* L. | C3 | Reduced |
| Lovegrass | *Eragrostis curvula* (Schrad.) Nees | C4 | Reduced |
| Quackgrass | *Elytrigia repens* (L.) Gould | C3 | Reduced |
| Redroot pigweed | *Amaranthus retroflexus* L. | C4 | None |
| Rhodes grass | *Chloris gayana* Kunth | C4 | Reduced |
| Smut grass | *Sporobolus indicus* (L.) R. Br. | C4 | None |

Adopted from Ziska, 2014; *Photosynthetic pathway

**Table 8**. Response of crop plants and weeds under elevated $CO_2$, increased temperature and prolonged drought periods

| | | | Climate change component | | |
|---|---|---|---|---|---|
| | Plant response | Result | $CO_2$* | Temperature | Drought |
| Crop plants | Root mass | Root:shoot ratio | + | | |
| | Leaf area | Interception of PAR** | + | | |
| | Leaf development | Leaf area | | - | |
| | Flowering | Vegetative stage | | - | |
| | Harvesting | Yield | | - | - |
| | Fruit production | Yield | | - | |
| | Vernalization | Vegetative stage | | - | |
| | Stomata conductance | Rate of photosynthesis | | - | - |
| | Stomata closure | WUE | | + | + |
| | $CO_2$:$O_2$ | Rate of photosynthesis | | | - |
| | Respiration rate | Biomass production | | + | |
| | Seed formation period | Yield | | - | |
| | Biomass production | Yield | + | - | - |
| | Node number | Biomass, height | | | - |
| Weeds | Stomata closure | WUE | + | | |
| | Maturity rate | Vegetative stage | + | | |
| | Root biomass | Root:shoot ratio | + | | |
| | Distribution | | | + | |
| | Vernalization | Vegetative stage | | - | |

| | | | | |
|---|---|---|---|---|
| | Biomass | | + | |
| | Seed germination*** | Distribution | + | |
| | Rhizomes*** | Distribution | + | |
| | Seed longevity | | | + |

*Elevated $CO_2$ favors, in most cases, C3 plant types; **photosynthetically active radiation; ***seed germination and rhizomes production, for most weed species, are affected negatively by low temperatures as it is mentioned in the text. Therefore, it is assumed that under relatively elevated temperatures will be affected positively. + and – signs indicate a positive or negative effect respectively.

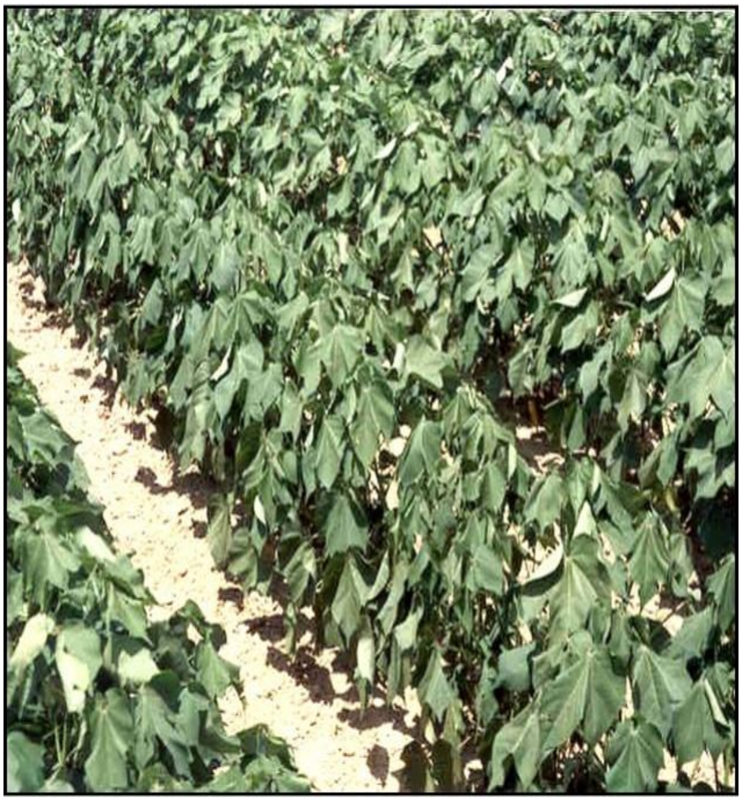
## Figure captions

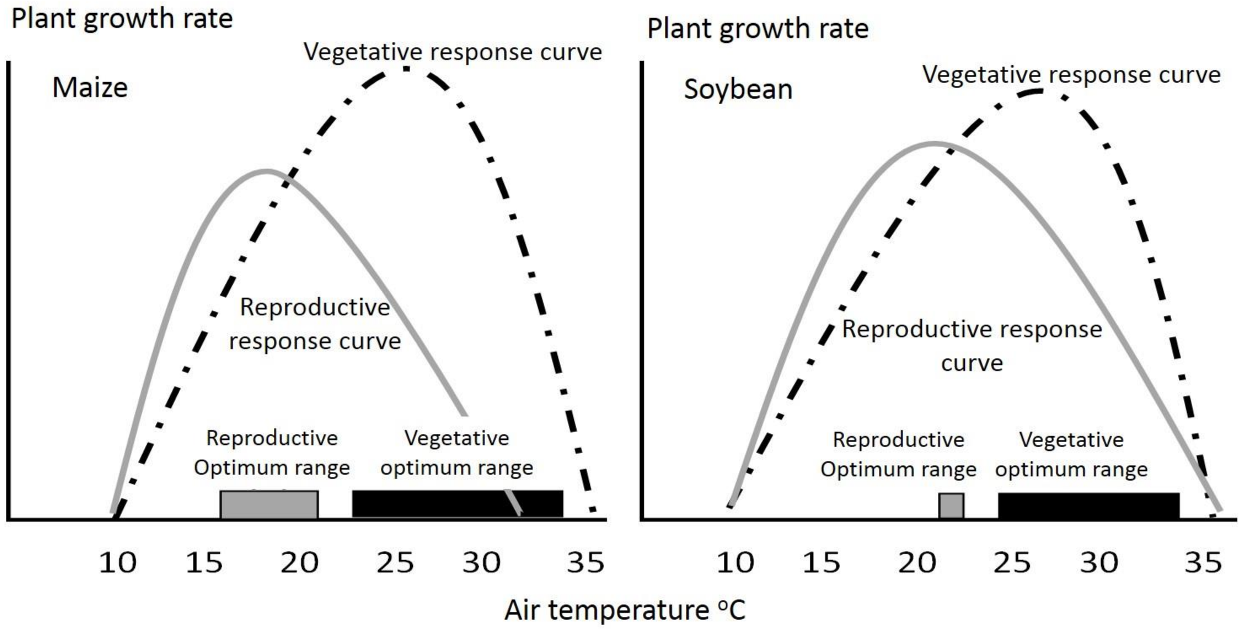
**Figure 1**. A water stressed cotton field (a) (with permission from D. M. Oosterhuis) and heavily infested cotton field by Palmer amaranth (b) (with permission from J. K. Norsworthy)

**Figure 2**. Vegetative and reproductive response of maize and soybean to temperature increases (based on Karl et al., 2009).

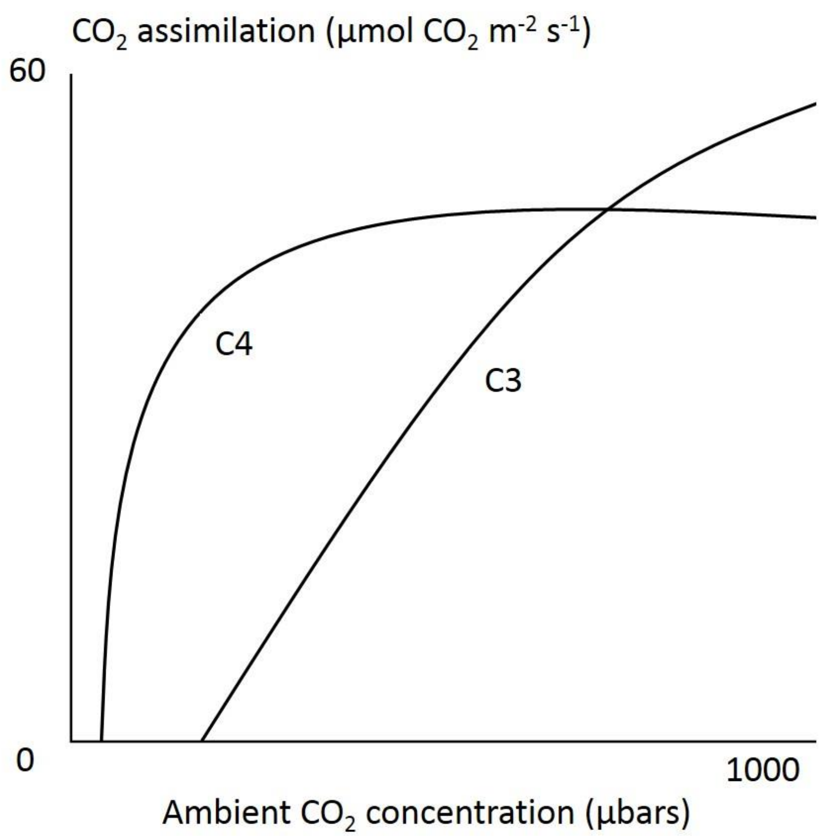
**Figure 3**. Response of $CO_2$ assimilation in C3 vs. C4 plants to increases in $CO_2$ concentration (based on Taiz and Zeiger, 1991).

**Figure 4.** Rice weed suppression plots at Stuttgart, Arkansas, USA in which the superior competitiveness of cultivars STG06L-35-061 and PI312777 compared with Katy and Lemont is shown. A "light" infestation of barnyardgrass can be observed in the former compared to later plots. No herbicide was used to control grass weeds (with permission from D. R. Gealy, USDA-ARS)".

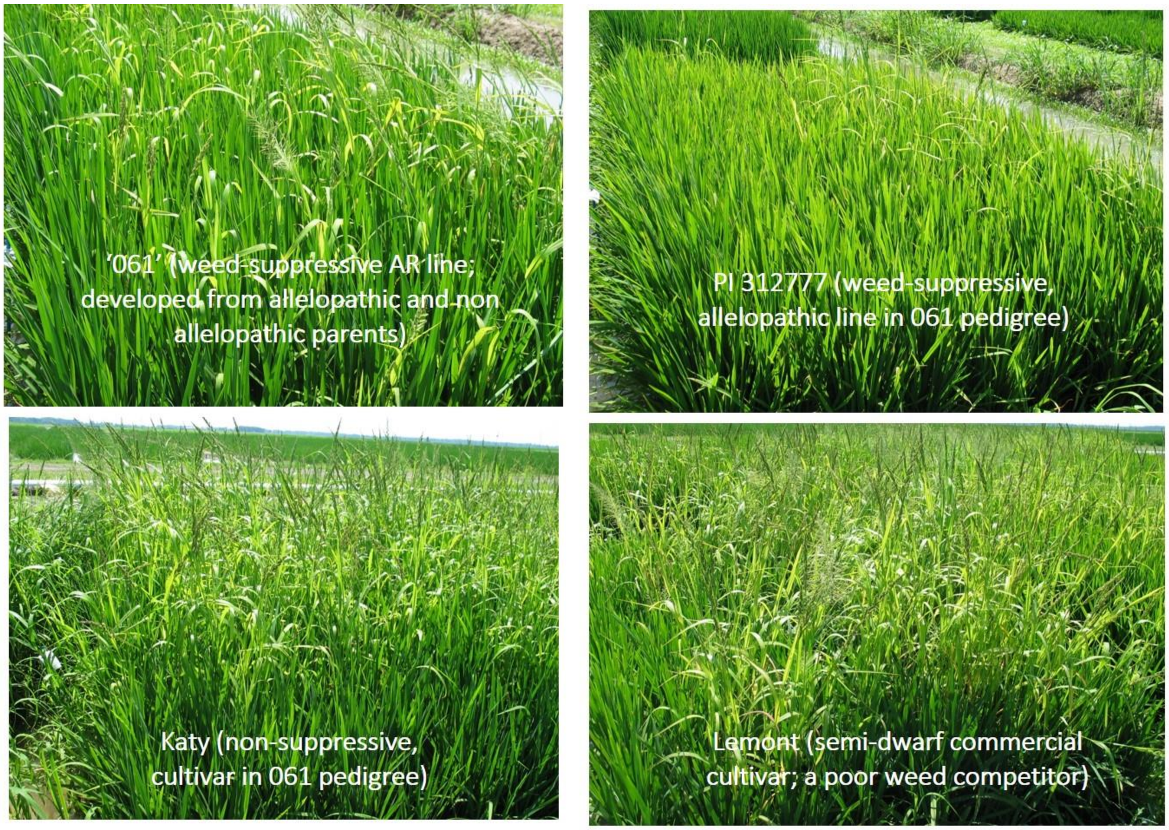




Plant growth rate
Maize
Vegetative response curve
Reproductive response curve
Reproductive Optimum range
Vegetative optimum range
Plant growth rate
Soybean
Vegetative response curve
Reproductive response curve
Reproductive Optimum range
Vegetative optimum range
10 15 20 25 30 35
10 15 20 25 30 35
Air temperature °C

CO2 assimilation (µmol CO2 m-2 s-1)
60
0
C4
C3
1000
Ambient CO2 concentration (µbars)


'061' (weed-suppressive AR line;
developed from allelopathic and non
allelopathic parents)
PI 312777 (weed-suppressive,
allelopathic line in 061 pedigree)
Katy (non-suppressive,
cultivar in 061 pedigree)
Lemont (semi-dwarf commercial
cultivar; a poor weed competitor)